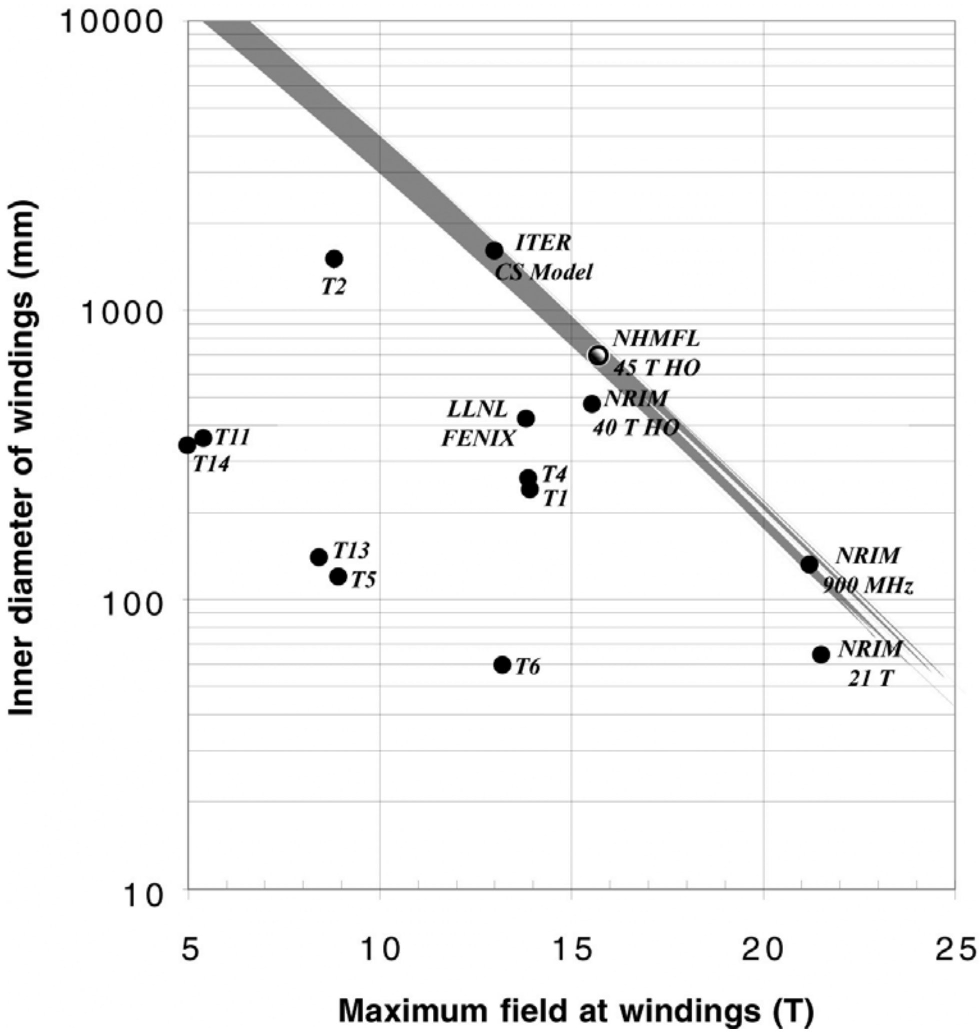
Hybrid Comparison Information

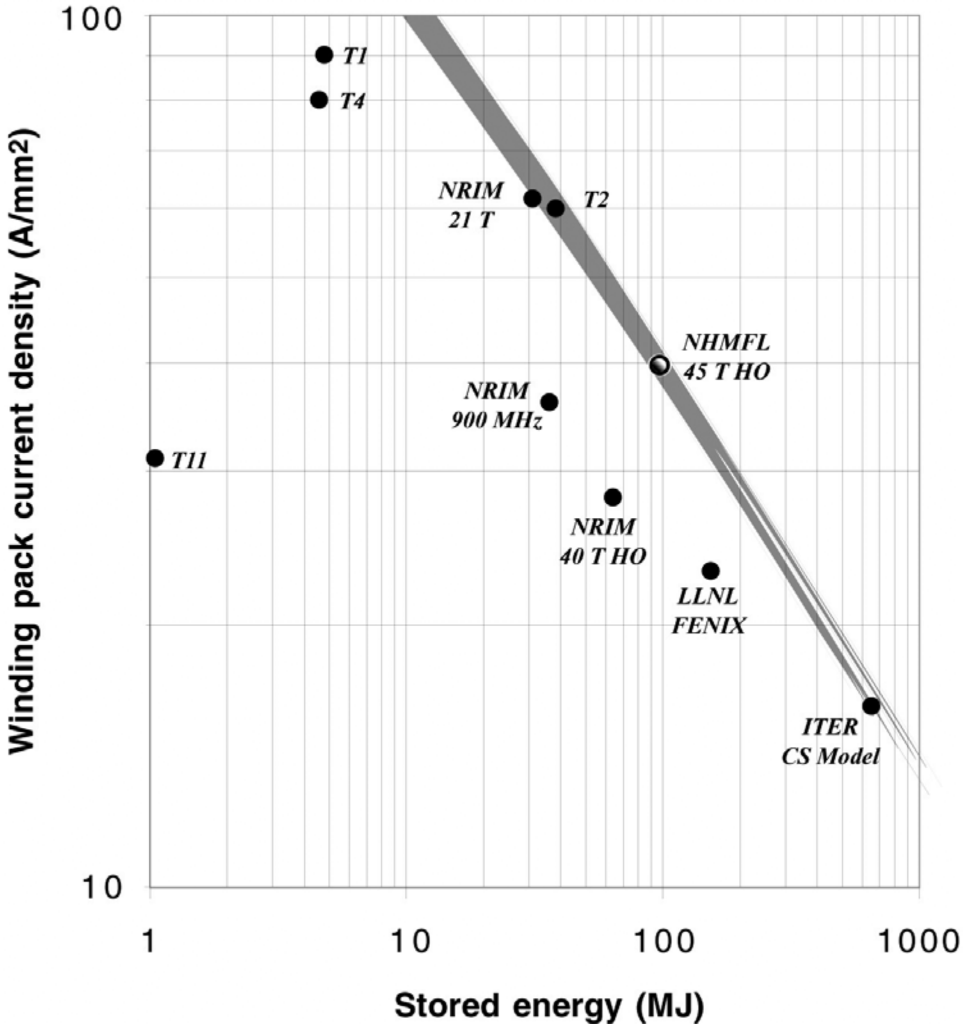
Much has been said to try to quantify the performance of the 45-T Hybrid (e.g. it produces almost a million times the earth's field, it stores over 100 MJ of energy in its magnetic field, the system weighs over 34 metric tons, etc.). Sometimes, these descriptions are not very satisfying. After all, pulsed magnets can produce higher field, there's more energy stored in a stick of dynamite, and a locomotive weighs more. Perhaps more satisfying comparisons can be made to other similar systems, upon which people (and funding agencies) have seen fit to expend significant resources. Since such projects are generally the subject of careful scrutiny, it is reasonable to expect that they give a useful perspective of the "state of the art" for the technology in question. In the graphs below, we try to make such comparisons for the superconducting outsert of the 45-T Hybrid. In table I, we provide a list of systems included with references. This list is not exhaustive but it is certainly representative of the highest achievements in recent years for a variety of applications; we arbitrarily limit consideration to magnets with maximum field greater than 5 T.

Among the many parameters that measure the difficulty of building a superconducting magnet, field production is the most often mentioned. But to the magnet designer, the maximum field at the windings is the more directly meaningful parameter. Of course, field alone does not fully measure the difficulty. As with many things, size matters. In Fig. 1, we present our group of systems with a simultaneous comparison of maximum field at the windings and inner diameter of the high-field windings. The level of difficulty increases as we move up and to the right on this graph, and the 45-T Hybrid Outsert is clearly on the frontier.

Stored energy is another very real measure of superconducting-magnet performance. It directly impacts the design through its relation to mechanical stresses in the windings and to requirements for protecting the magnet should it be necessary to extract or dissipate that energy suddenly. Typically, design features to accommodate the stored energy (e.g. distributed structure or integral shunt material in the conductor) result in lower current densities in the windings than would otherwise be achievable. In Fig. 2, the systems displayed for simultaneous comparison of stored energy and winding pack current density. Note that many of these systems have "graded" windings, wherein several levels of windings are included – with different conductor choices or different structural content, etc. In these cases, the winding-pack current density in the innermost or high-field winding was chosen to represent the system. As in Fig. 1, the more difficult domain is up and to the right, and again the 45-T Hybrid Outsert is at the frontier.

Item	Description/Intended Use	Reference
T1	DC solenoid/Conductor testing	Tsukamoto et al., IEEE Trans. Applied Superconductivity, Vol 9, no. 2, p. 547 (1999).
T2	DC solenoid/Conductor testing	*ibid*
T4	DC solenoid/Conductor testing	*ibid*
T5	DC split solenoid/Conductor testing	*ibid*
T6	DC solenoid/Conductor testing	*ibid*
T11	DC pancake module/SMES development	*ibid*
T13	DC solenoid/SMES development	*ibid*
T14	Pulsed pancake module/SMES development	*ibid*
NRIM 40T HO	DC solenoid/Research facility	Morita et al., in High Magnetic Fields: Applications, Generation, and Materials, Schneider-Muntau ed., World Scientific, Singapore, p. 333 (1997)
NHMFL 45T HO	DC solenoid/Research facility	
FENIX	DC split solenoid/Conductor testing	Slack et al., IEEE Trans. Magnetics, Vol. 27, no. 2, p. 1835 (1991).
CS Model Coil	Pulsed solenoid/Technology demonstration	H. Tsuji, JAERI, private communication, 19 April 2000.
NRIM 21T	DC solenoid/Research facility	Hirose et al., Proceedings of the 15th International Conference on Magnet Technology (MT15), Bejing, Peoples Republic of China, October 20 - 24, 1997.
NRIM 900 MHz	DC solenoid/Research facility	Kiyoshi et al., IEEE Trans. Applied Superconductivity, Vol. 9, no. 2, p. 559 (1999) and T. Kiyoshi, NRIM, private communicaton, 6 March 2000.


10000
1000
100
10
5
10
15
20
25
Inner diameter of windings (mm)
Maximum field at windings (T)
ITER
CS Model
T2
NHMFL
45 T HO
NRIM
40 T HO
LLNL
FENIX
T11
T14
T4
T1
T13
T5
NRIM
900 MHz
T6
NRIM
21 T



Winding pack current density (A/mm²)
100
10
1
10
100
1000
Stored energy (MJ)
T1
T4
NRIM
21 T
T2
NHMFL
45 T HO
NRIM
900 MHz
T11
NRIM
40 T HO
LLNL
FENIX
ITER
CS Model